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LIFE PREDICTION MODELING BASED ON STRAINRANGE PARTITIONING

Gary R. Halford
Fatigue and Fracture Branch
NASA Lewis Research Center

ABSTRACT

Strainrange partitioning (SRP) is an integrated low-cycle-fatigue life prediction system. It was created by Manson et al. (1971) specifically for calculating cyclic crack initiation life under severe high-temperature fatigue conditions. The system has received exhaustive evaluation by Lewis personnel, contractors and grantees, and numerous independent industrial and research organizations around the world. Improvements and additions have been incorporated continuously, including some within the past year. The key feature of the SRP system is its recognition of the interacting mechanisms of cyclic inelastic deformation (i.e., strainrange) that govern cyclic life at high temperatures. Time-dependent, thermally activated deformation processes and time-independent dislocation glide, and their relative contributions (i.e., partitioning) within each strain cycle significantly affect fatigue crack initiation life. The SRP system is the engineering quantification, at the macroscopic level, of these microscopic influences on high-temperature fatigue life. For example, at the macroscopic engineering level, the micromechanisms of deformation are lumped into two major phenomenological categories, either creep (and attendant oxidation) or plasticity deformation.

The SRP system bridges the gap between the mechanistic level of understanding that breeds new and better materials and the phenomenological level wherein workable engineering life prediction methods are in great demand.

The system has recently been expanded to address engineering fatigue problems in the low-strain, long-life, nominally elastic regime. This breakthrough, along with other advances in material behavior and testing technology, has permitted the system to also encompass low-strain thermomechanical loading conditions. This is a critical durability problem area for a great number of engineering structural components subjected to high-temperature service.

Other important refinements of the originally proposed method include procedures for dealing with life-reducing effects of multiaxial loading, ratchetting, mean stresses, nonrepetitive (cumulative damage) loading, and environmental and long-time exposure. Procedures have also been developed for partitioning creep and plastic strains and for estimating strainrange-versus-life relations from tensile and creep-rupture properties.

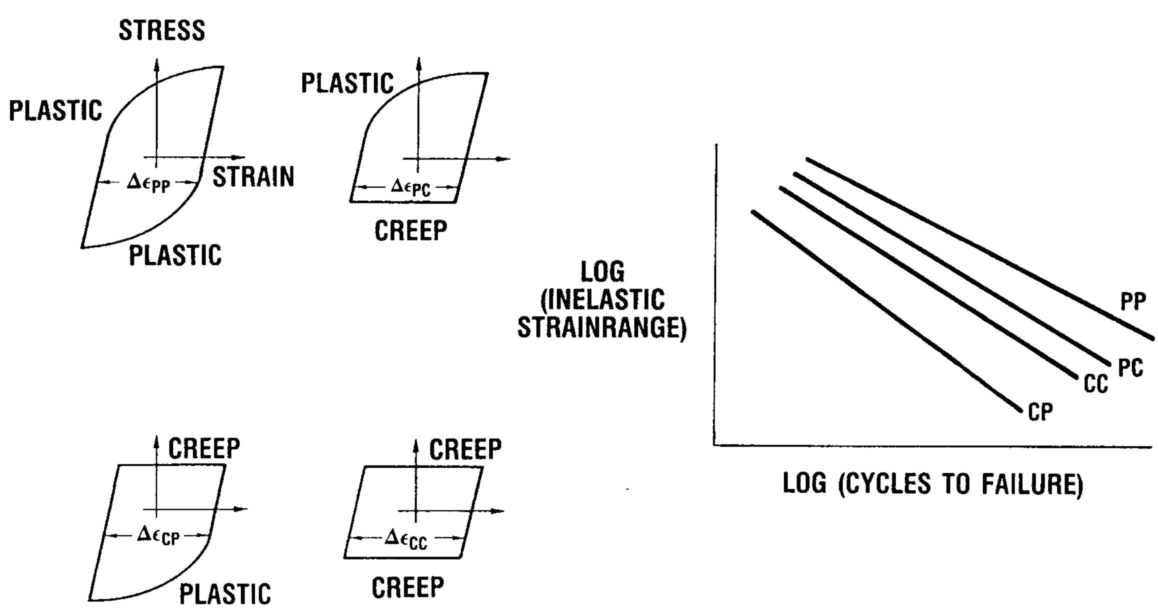
Each of the important engineering features of the SRP system are discussed and examples shown of how they help toward predicting high-temperature fatigue life under practical, although complex, loading conditions.

OVERVIEW

ORIGINAL BASIS OF SRP

Strainrange partitioning is an integrated system for calculating cyclic crack initiation life under severe high-temperature fatigue conditions. The key feature of the SRP system is its recognition of the interacting creep and plasticity mechanisms of cyclic inelastic deformation that govern cyclic life at high temperatures. Recent developments now permit the system to deal also with interactions due to effects of high-temperature oxidation. SRP has received extensive evaluation at Lewis, by contractors and grantees, and at numerous independent industrial and research organizations around the world. Improvements and additions are constantly being brought into the system.

The basics of SRP as it was first proposed several years ago are known to many and are illustrated below only for completeness. Since the introduction of SRP, it has been constantly improved upon in efforts to overcome recognized deficiencies. Despite its many improvements the basic concept remains valid and unchanged - the primary variable that governs low-cycle-fatigue life at high temperatures is the magnitude of the inelastic strainrange and the manner in which the time-dependent and time-independent inelastic deformations reverse themselves within a complete cycle. In the extreme there are only four different cycles that combine these two strain types in tension and compression loading. Each will potentially have its individual set of deformation mechanisms, and hence strainrange-versus-life relations, that are generalizations of the classical Manson-Coffin law of low-cycle fatigue.



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CURRENT MODULES IN SRP SYSTEM

The numerous improvements to the SRP system are listed below and discussed in the text that follows. Each item is discussed from the standpoints of why the improvement was needed, how the improvement is implemented, the quantitative benefits of the improvement, and finally what remains to be done for further improvement.

The SRP system of life prediction has been created in a modular fashion, and a module is called upon only if the problem at hand warrants. In applying the system to the life prediction of a structural component, certain inputs are required from the structural analysis. These include the stress-strain-temperature-time history at the critical crack initiation location. Obviously the strainrange-versus-life relations for the material must also be known through measurement or estimation.

To date the SRP system has not been codified for computer application.

- **BOUNDING LIFE AND TEMPERATURE INSENSITIVITY**
- **MULTIAXIAL EFFECTS**
- **MEAN STRESS EFFECTS**
- **CREEP AND PLASTIC RATCHETTING**
- **CUMULATIVE CREEP-FATIGUE DAMAGE**
- **DUCTILITY-NORMALIZED LIFE RELATIONS**
- **ENVIRONMENTAL AND LONG-TIME EXPOSURE EFFECTS**
- **TOTAL STRAINRANGE VERSION**
- **THERMOMECHANICAL FATIGUE**

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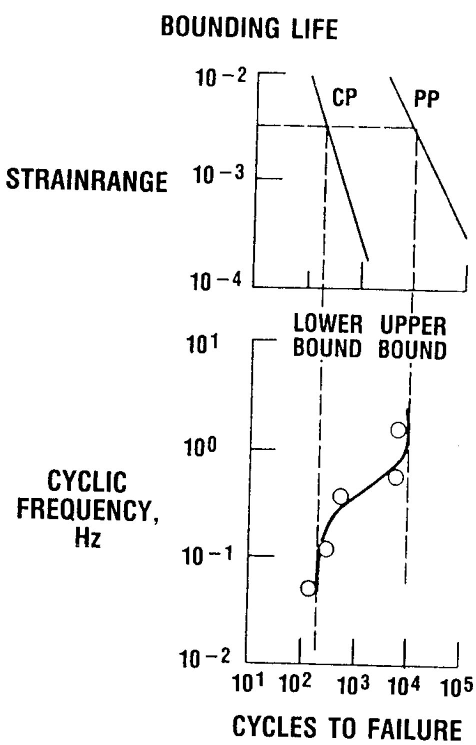
POSTER PRESENTATION

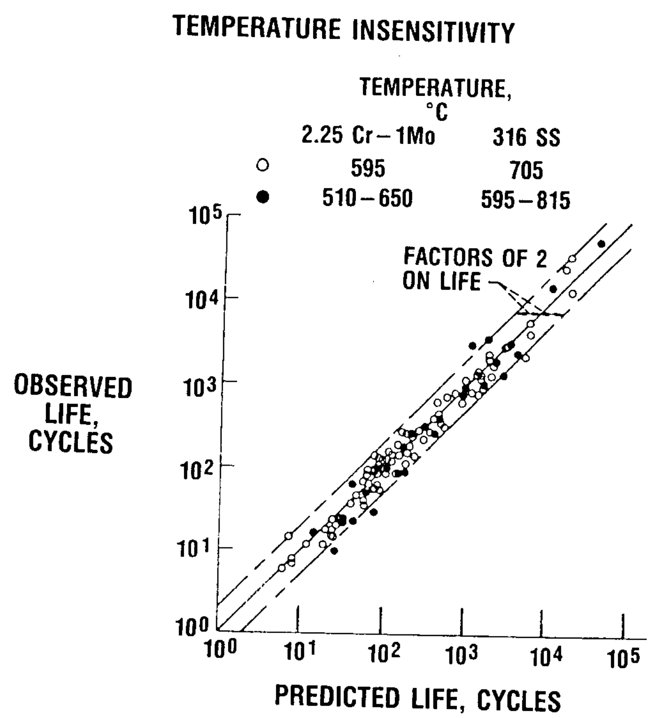
BOUNDING LIFE AND TEMPERATURE INSENSITIVITY

Two distinct features of the SRP system that offer significant advantages in performing engineering creep-fatigue life predictions are (1) the ability to provide upper and lower bounds on expected cyclic life with only limited analysis, and (2) the insensitivity to temperature of the life relations.

Upper and lower bounds on expected cyclic life for an imposed inelastic strainrange are given by the example figure on the left (Hirschberg and Halford, 1976). Typically the upper bound is given by the plastic-plastic (PP) life relation. The lower bound, although frequently being the creep-plastic (CP) life relation for materials that crack and fail intergranularly, could be the plastic-creep (PC) or creep-creep (CC) life relation, depending on which is the most damaging for the material in question.

Temperature insensitivity applies to materials whose creep-fatigue deformation mechanisms are not altered appreciably over a broad temperature range. This includes a large number of metallurgically stable engineering alloys whose creep and tensile ductilities remain reasonably constant over the temperature range of interest. The advantage to the analyst is in the reduced amount of temperature-dependent failure data that are needed to document the life equations. A secondary benefit is obtained from the reduced accuracy required in identifying the operating temperature. The graph on the right below illustrates the temperature insensitivity of strainrange-versus-life relations for two engineering alloys (Halford et al., 1973).





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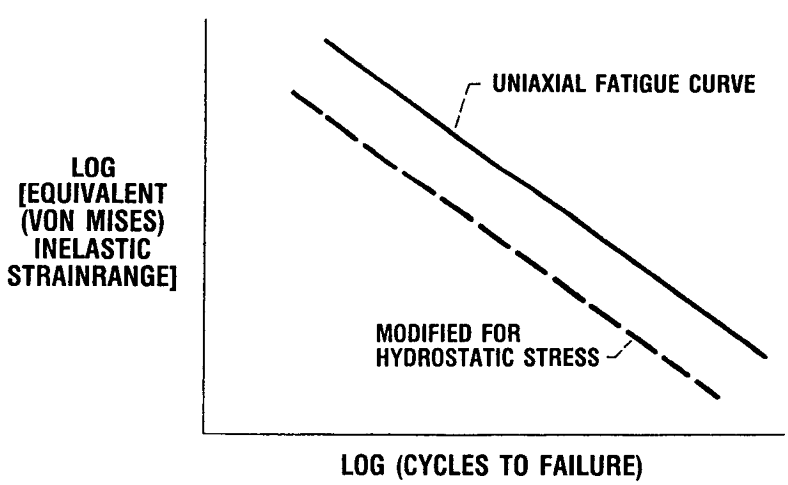
MULTIAXIAL EFFECTS

Multiaxial stress and strain states pose several special problems for creep-fatigue life prediction. Since most creep-fatigue results are generated for uniaxially loaded specimens, and quite rarely for multiaxial stress-strain states, the designer must rely on a multiaxial failure theory to relate complex states of loading to the simple uniaxial state. A relatively simple procedure for dealing with this problem was proposed by Manson and Halford (1977). The procedure involves using the von Mises theory for the distortional component of strain, and a multiaxiality factor for the hydrostatic component of stress. The greater the tensile hydrostatic state of stress, the lower the potential ductility, and hence the lower the strainrange-versus-life relations.

In addition, the concepts of "tension" and "compression" deformation for simple uniaxial loading must be generalized for multiaxial loadings in which both tensile and compressive stresses appear simultaneously but along different directions. Since the SRP system recognizes that the damaging nature of a cycle of inelastic strain at high temperatures depends strongly on whether the strains are tensile or compressive, the concept of tension and compression must be retained in any multiaxial creep-fatigue theory to be used by SRP. Procedures to establish dominant directions for classifying a stress-strain state as being predominantly tension or compression have been suggested by Manson and Halford (1976). The procedures apply to proportional multiaxial loading. Rules were not given for nonproportional loading because of the dearth of data to serve as a guideline. Limited experimental verification has been achieved to date for the multiaxial module in the SRP life prediction system.



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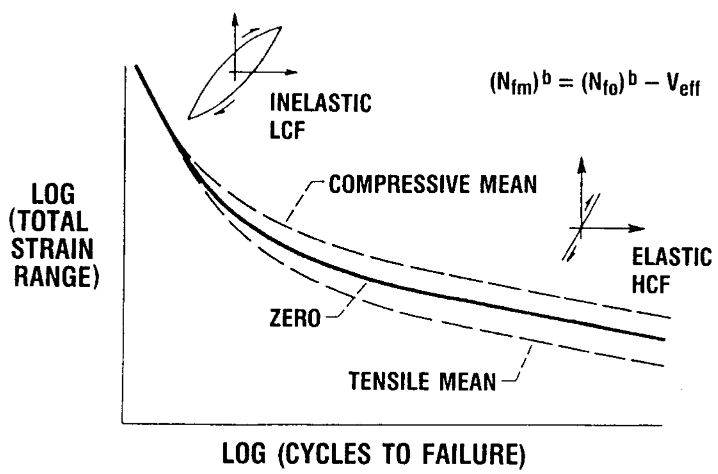
MEAN STRESS EFFECTS

Although mean stress effects are usually associated with high-cycle fatigue, they are almost always present in high-temperature, low-cycle fatigue. In past years such mean stresses have been ignored. However, research at the Lewis Research Center has indicated that such stresses cannot always be ignored. Halford and Nachtigall (1980) developed a criterion for establishing the effectiveness of mean stresses under isothermal creep-fatigue conditions. The effectiveness criterion was used in conjunction with the Morrow equation (Morrow, 1968) for describing the Goodman diagram for mean σ_m and alternating σ_a stresses in fatigue. The equation has been recast in terms of the life N_{fm} with and N_{fo} without mean stress, the slope of the high-cycle-fatigue curve, and the mean stress ratio (V = mean/alternating). The principal feature of the criterion is that a transition period exists between high-cycle fatigue (nominally elastic stress-strain response), where the mean stress effect is 100 percent, and lower-cycle fatigue, where large inelastic strains nullify the mean stress effect. The isothermal mean stress equation is shown below. The constant, 70, was evaluated for the disk alloys, AF2-1DA and IN-100. Under thermal fatigue conditions, additional considerations must be examined since mean stresses can develop because of the temperature-dependent stress-strain characteristics of a material. Halford (1987) suggests a procedure for determining mean stress effectiveness under thermal cycling conditions. The terms are completely defined in the Halford (1987) paper.



ISOTHERMAL:

$$V_{eff} = V_\sigma \exp\left[-70\left(\frac{\Delta\epsilon_{in}}{\Delta\epsilon_{el}}\right)^2\right]$$

THERMOMECHANICAL:

$$V_{eff} = \frac{1 + \dfrac{R_\sigma}{R_y}}{1 - \dfrac{R_\sigma}{R_y}}$$

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CREEP AND PLASTIC RATCHETTING

The damaging nature of creep or plastic ratchetting strains has received very little attention by researchers. Theoretical considerations have been nil, and few well-controlled experiments have been conducted. To provide a first-order approximation as to the damage imparted by ratchetting strains, an SRP system module has been adopted (Manson and Halford, 1976) that uses a simple linear exhaustion-of-ductility concept. Plastic ratchetting strain δ_P exhausts tensile ductility D_P; creep ratchetting strain δ_C exhausts creep ductility D_C. The general inelastic strainrange SRP life equation for reversed strainrange damage and ratchetting strain damage is shown below. It is based on the interaction damage rule.

$$\text{DAMAGE CYCLE} = \underbrace{\frac{F_{PP}}{N_{PP}} + \frac{F_{CC}}{N_{CC}} + \frac{F_{CP}}{N_{CP}} + \frac{F_{PC}}{N_{PC}}}_{\text{CREEP-FATIGUE DAMAGE}} + \underbrace{\frac{\delta_P}{D_P} + \frac{\delta_C}{D_C}}_{\text{RATCHETTING DAMAGE}} = \frac{1}{N_F}$$

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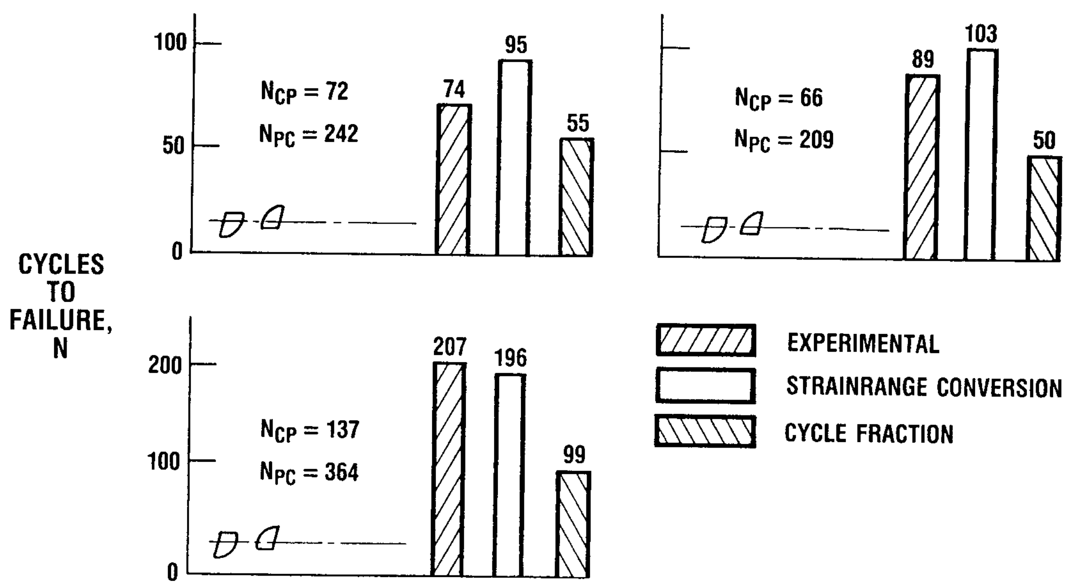
CUMULATIVE CREEP-FATIGUE DAMAGE

Cumulative creep-fatigue damage theories are in their infancy compared with lower temperature fatigue damage models. Creep-fatigue damage experimentation is also in its formative years. The SRP creep-fatigue life prediction system uses the recently proposed concept (Manson and Halford, 1983) called strain-range conversion. As a simple example to illustrate the concept, consider a repeating series of cycles in which each CP cycle is followed immediately by a PC cycle. Both strainranges are considered to be "unbalanced" since the tensile and compressive strains are different in each case. For alloys such as austenitic stainless steels, CP strainranges are more damaging, by about an order of magnitude, than PC strainranges. Thus from the CP strainrange alone one would expect (based on a simple cycle fraction approach) the block of CP + PC cycles to result in a block life that is always less than the number of cycles to failure. However, if this repeating series is shifted by one-half cycle of loading, it could be represented as a repeating series of CC-PP cycles. This sequence involves "balanced" cycles, which are generally less damaging than unbalanced ones. Since this sequence is actually the same as the first (with the exception of exactly one-half cycle), the experimental lives of the two will be the same. However, for the second sequence the "expected" number of blocks of loading (based on cycle fraction) should be greater than for the first sequence, since CC and PP strainrange damages are considerably more benign. The number of blocks should also be less than the number of CC cycles to failure, and more importantly, greater than the original number of CP cycles to failure. The principle of strainrange conversion (SRC) addresses the seeming contradiction in reasoning noted above and provides the rationale for synthesizing any series of SRP strain cycles.



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DUCTILITY-NORMALIZED LIFE RELATIONS

The four SRP inelastic strainrange-versus-life relations may not be available for a particular material. Therefore a set of equations has been derived for estimating them from a knowledge only of a material's tensile plastic ductility D_P and creep ductility D_C. The equations are known as the ductility-normalized strainrange partitioning life relations (DN-SRP). The constants in these equations were determined empirically from a large number of data sets on a variety of alloy systems (Halford et al., 1977). Note that two equations exist for estimating the CP strainrange-versus-life relation. The first is for transcrystalline creep cracking alloys, and the second for intercrystalline creep cracking alloys.

The life relations estimated by the DN-SRP equations shown below are in agreement with measured life relations to within a factor of approximately 3 in cyclic life. The greater the ductility, the greater the resistance to failure by cyclic inelastic deformation. These equations also help to predict whether the strainrange-versus-life relations are sensitive to test temperature. If the ductility of an alloy does not change appreciably with temperature, the strainrange-versus-life relations will probably also be insensitive to test temperature.

$$\Delta\epsilon_{PP} = 0.50\ D_P (N_{PP})^{-0.60}$$

$$\Delta\epsilon_{PC} = 0.25\ D_P (N_{PC})^{-0.60}$$

$$\Delta\epsilon_{CC} = 0.25\ (D_C)^{0.60} (N_{CC})^{-0.60}$$

$$\Delta\epsilon_{CP} = 0.20\ (D_C)^{0.60} (N_{CP})^{-0.60} \text{ (TRANSCRYSTALLINE)}$$

OR

$$\Delta\epsilon_{CP} = 0.10\ (D_C)^{0.60} (N_{CP})^{-0.60} \text{ (INTERCRYSTALLINE)}$$

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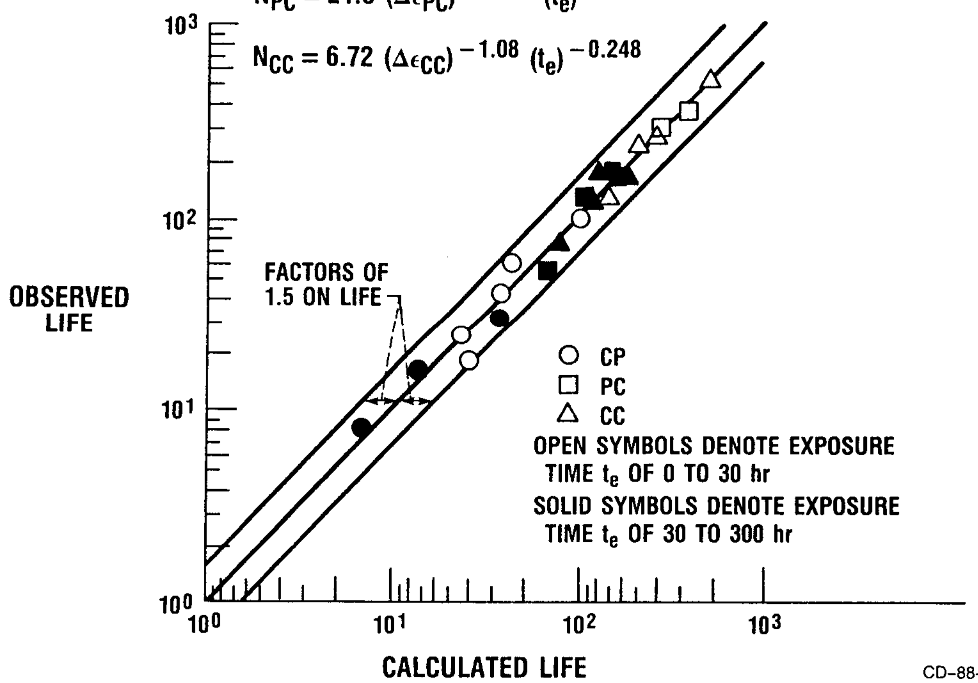
Procedures based on modification of the inelastic strainrange-versus-life relations have been proposed by Kalluri (1987) and Kalluri et al. (1987) to account for oxidation of alloys and other time-dependent degradation mechanisms. Excellent correlations of experimental results have been obtained with the modified life relations. Two forms of time-dependent strainrange-versus-life relations are available to choose from, depending on the information available to the user. One set is written in terms of the time of exposure, while the other is in terms of steady-state creep rates associated with the stresses encountered in a cycle. For brevity, only the exposure-time relations are shown here. An example set of equations for CP, PC, and CC inelastic strainranges are shown below for type 316 austenitic stainless steel evaluated at 816 °F. Exposure times are from a few minutes to about 300 hours. These equations have been highly effective in correlating time-dependent effects as indicated in the figure. Correlation of the experimental results to within a factor of only 1.5 in cyclic life is considered exceptionally good.

EXPOSURE-TIME-MODIFIED STRAINRANGE-VERSUS-LIFE RELATIONSHIPS

$$N_{CP} = 0.113\,(\Delta\epsilon_{CP})^{-1.63}\,(t_e)^{-0.332}$$

$$N_{PC} = 21.8\,(\Delta\epsilon_{PC})^{-0.696}\,(t_e)^{-0.223}$$

$$N_{CC} = 6.72\,(\Delta\epsilon_{CC})^{-1.08}\,(t_e)^{-0.248}$$



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TOTAL STRAINRANGE VERSION

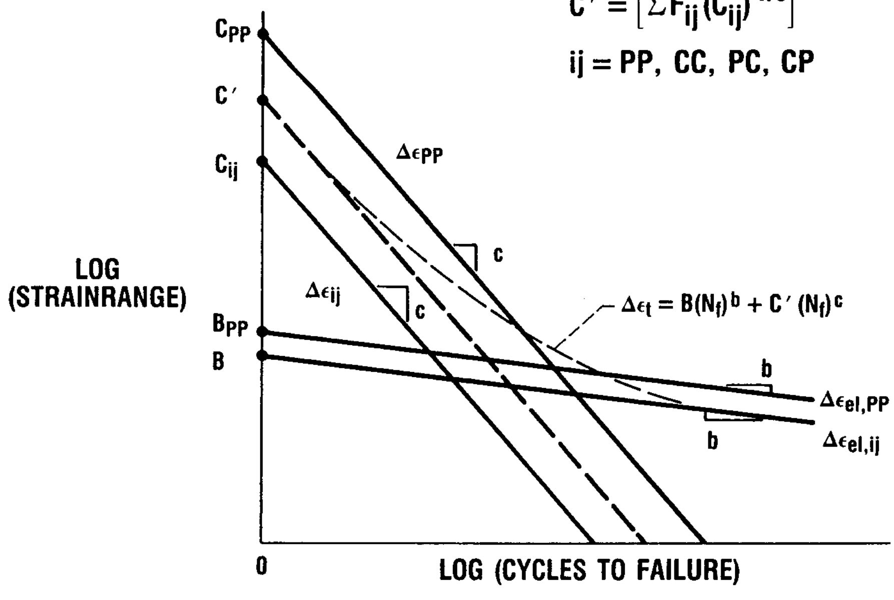
A workable total strainrange version of strainrange partitioning (TS-SRP) was first proposed by Halford and Saltsman (1983). Improvements have been made recently (Saltsman and Halford, 1988a). The TS-SRP module of the SRP life prediction system was designed to overcome the problems of applying SRP to the low-strain, long-life, nominally elastic regime of low-to-intermediate cycle fatigue. In that regime direct application of the classical inelastic strainrange-versus-cyclic-life relations of SRP is virtually impossible. The calculation accuracy would be totally unacceptable. In applying the TS-SRP version an alloy is characterized in much the same manner as for the original inelastic strainrange version. However, additional information concerning cyclic stress-strain characteristics is needed along with elastic strainrange-versus-cyclic-life data. Thus advantage is taken of recent advances made in the development of unified constitutive equations relating cyclic stresses, strains, temperature, and time. Using the TS-SRP module allows the life of a structural component to be calculated from the magnitude of the total strain response in the structure at the critical crack initiation location. The strain-time waveshape of the repetitive cycle is used in conjunction with a unified constitutive model to determine the partitioning of whatever inelastic strains may be present. The constitutive model along with pre-existing material property correlations can be used to identify the equation of the elastic strainrange-versus-cyclic-life relation that is to be added to the partitioned inelastic strainrange-versus-life relation to form the total strainrange-versus-life relation. It is this life relation that is entered by using the total strainrange determined for the critical location. Never once in the processes is it necessary to actually identify the magnitude of the inelastic strainrange. Example applications of TS-SRP to complex loadings of laboratory specimens has been provided by Moreno et al. (1985).

$$\Delta\epsilon_{el} = B(N_{fo})^b$$

$$\Delta\epsilon_{in} = C'(N_{fo})^c$$

$$C' = \left[\Sigma F_{ij}(C_{ij})^{1/c}\right]^c$$

$$ij = PP,\ CC,\ PC,\ CP$$



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THERMOMECHANICAL FATIGUE

Thermomechanical fatigue problems pose special requirements for life prediction methods. Efforts to base thermomechanical fatigue life prediction methods on isothermal creep-fatigue behavior have not always met with success. The reason is that the thermal history of a thermal fatigue cycle can activate cyclic deformation and crack initiation mechanisms that simply are not present in isothermal strain cycles. To overcome this difficulty in a manageable manner, Saltsman and Halford (1988b) proposed that the life relations for the TS-SRP module be determined from tests involving two distinctly different isothermal temperatures -- one high and one low. This type of test has been termed the "bithermal fatigue test" and is reported upon in this conference by M.J. Verrilli. By using the bithermal test, it is possible to generate inelastic strainrange-versus-life relations for the unbalanced cycles of CP (in phase) and PC (out of phase). Almost all thermal and thermomechanical fatigue cycles are of the unbalanced type (i.e., the tensile and compressive paths of the cycle are not the same). It is also possible to perform bithermal PP tests by the proposed technique. Results of applying the TS-SRP module to thermomechanical fatigue for two engineering alloys, the cast nickel-base superalloy B1900 and the wrought cobalt-base alloy Haynes 188, are to be reported upon in June by Halford et al. (1988).

- **BITHERMAL STRAINRANGE-VERSUS-LIFE RELATIONS**
- **UNIFIED CONSTITUTIVE MODELING**
- **TOTAL STRAINRANGE VERSION (TS-SRP)**

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